Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-65-TR–2003/38 September 2003

Survivability, Structures, and Materials Directorate

Technical Report

SIDER Testing of a Damaged Section of Mast from the *Mirabella V* Superyacht

by

Colin P. Ratcliffe, *United States Naval Academy*

Roger M. Crane, *Naval Surface Warfare Center*

NSWCCD-65-TR–2003/38 SIDER Testing of a Damaged Section of Mast from the *Mirabella V* Superyacht

DEPARTMENT OF THE NAVY

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SUBJ: STRUCTURAL IRREGULARITY AND DAMAGE EVALUATION ROUTINE (SIDER) INSPECTION OF SHIP STRUCTURES

Ref: (a) Composite High-Speed Vehicle Task for FY03, Program Element 0603236N

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1. Reference (a) requested the Naval Surface Warfare Center, Carderock Division (NSWCCD) to conduct SIDER inspections of various ship hulls and components. This effort is in support of The Technical Cooperation Program (TTCP), composite panel TP-7, Operating Assignment 026, on the durability assessment of composites in the service environment. This is part of KTA-10, composite performance and long-term durability under dynamic, thermal and shock loading. Enclosure (1) presents the results of a single SIDER inspection of the mast from the *Mirabella V* superyacht.

2. Comments or questions may be referred to Dr. Roger M. Crane, Code 6553; telephone (301) 227-5126; e-mail, CraneRM@nswccd.navy.mil.

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Subj: STRUCTURAL IRREGULARITY AND DAMAGE EVALUATION ROUTINE (SIDER) INSPECTION OF SHIP STRUCTURES

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Enclosure (1)

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14. ABSTRACT
This report documents work performed by the Naval Surface Warfare Center, Carderock Division in support of The Technical Cooperation Program (TTCP), composite panel TP-7, Operating Assignment 026, on the durability assessment of composites in the service environment. This is part of KTA-10, composite performance and long-term durability under dynamic, thermal and shock loading. This report presents the results of a single Structural Irregularity and Damage Evaluation Routine (SIDER) inspection of one section of the new mast of the Mirabella V superyacht. The section that was tested had known manufacturing defects. Prior to the SIDER testing, the decision had been made by VT Halmatic Limited, Portchester Shipyard, Hamilton Road, Portsmouth, UK to remake the component. Therefore, the work reported here was conducted on a structurally unacceptable component that was not going to be used in service.

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Contents

Figures

Table

Page

Administrative Information

The work described in this report was performed by the Structures and Composites Department (Code 65) of the Survivability, Structures and Materials Directorate at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The work was funded by the Chief of Naval Research (ONR 334) as part of the Composite High-Speed Vehicle Task for FY03, Program Element 0603236N.

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The authors wish to acknowledge Pat Potter, ONR Code 334, for the financial support for this effort and Dr. Ignacio Perez, ONR Code 332, for his financial support during the earlier development of the SIDER technique. The authors would also like to acknowledge Dr. Paul Curtis, DSTL Farnborough, Alan Daniel, Warship Support Agency, and Alan Groves, MoD Abbeywood for organizing the logistics in support of the United Kingdom testing. Finally, we would like to thank Ajay Kapadia, Richard Littler, Graham Foord and Tom Pope of VT Halmatic for excellent local support during testing.

Background and Introduction

This report presents the results of a single Structural Irregularity and Damage Evaluation Routine (SIDER) inspection of one section of the new mast of the *Mirabella V* superyacht. The section that was tested had known manufacturing defects. Prior to the SIDER testing, the decision had been made by VT Halmatic Limited, Portchester Shipyard, Hamilton Road, Portsmouth, UK to remake the component. Therefore, the work reported here was conducted on a structurally unacceptable component that was not going to be used in service.

The owner of *Mirabella V* is Mr. Joseph Vittoria, Jr, and the designer is Ron Holland Design. *Mirabella V* is currently under construction by Vosper Thornycroft, Southampton, UK. The mast is under construction by VT Halmatic Limited, where we SIDER tested the mast section. Once completed, *Mirabella V* will be the largest single-masted yacht in the world. It will have an overall length of 247 feet (75.22 m), with a beam of 48.5 feet (14.80 m) and a draught of 33 feet (10.0 m). The half load displacement is 751 long tons (765 tonnes). The yacht has a lifting keel weighing 150 tonnes. When lifted, the draught is reduced to 13 feet (4.0 m). For comparison, Figure 1 and Figure 2 show an artist's impression of the yacht superimposed on the USS *John S. McCain* (DDG-56), an *Arleigh Burke*-Class destroyer, and the USS *Nimitz* (CVN-68).

Figure 1. Artist's Impression of *Mirabella V* Compared with USS *John S. McCain*

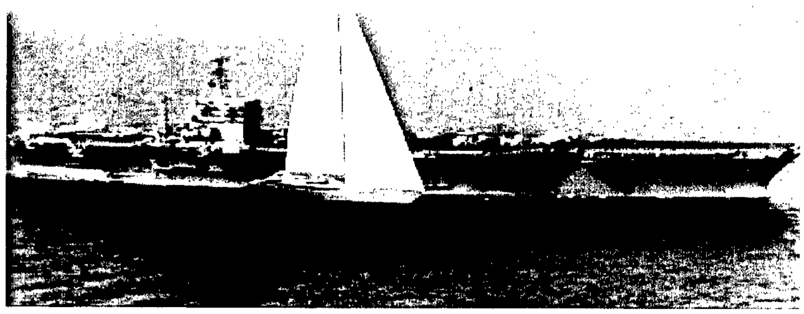


Figure 2. Artist's Impression of *Mirabella V* Compared with USS *Nimitz*

In early November 2002, The Technical Cooperation Program (TTCP) composite panel TP-7 had their annual meeting at the United States Naval Academy. One of the study assignments presented was Study Assignment 29 on the durability assessment of composites in the service environment. This is part of the KTA-10: Composite performance and long term durability under dynamic, thermal and shock loading. The presentation described the Structural Irregularity and Damage Evaluation Routine (SIDER), which is currently being developed at the United States Naval Academy and NSWC, Carderock Division by Drs. Colin Ratcliffe and Roger Crane, respectively.

There was significant interest in this technology and the ability of the SIDER to locate areas of structural differences in complex composite structures. The interest by the member countries was significant enough that the study assignment was elevated to an operating assignment. In this, the member nations work together in the development and transfer of the technology for the mutual benefit of the military of each nation.

In late November 2002, Dr. Paul Curtis, the UK National Leader, contacted Dr. Crane and expressed interest by Alan Groves from the MoD at Abbeywood (Bristol) to use SIDER to inspect a GRP hull and sandwich decking on an *Archer*-Class vessel. There have been issues of bonding of the deck to the hull on some ships in this class. It was requested that Drs. Ratcliffe and Crane contact Alan Daniel to discuss the possibility of going to the UK and inspecting the vessels with SIDER.

After several conference calls between the U.S. representatives and representatives of the MoD, it was decided that the SIDER technique may have the capability of locating damage in the *Archer*-Class decks, as well as other composite ship components. While Drs. Ratcliffe and Crane were in the United Kingdom testing an Archer class vessel, the opportunity was taken to visit VT Halmatic Limited, and test a component of the *Mirabella V* mast. The mast is constructed in five parts. There are two for the aft side, and three for the forward side. The section that was tested was part number five, being the lower-forward part. This was 120 feet long. The section is identified in Figure 3. Figure 4 shows general views of the mast section during testing in the facilities at VT Halmatic Limited, Portsmouth, United Kingdom, approximately located at 50° 50.72' N 001° 06.95' W. Testing took place on July 18, 2003.

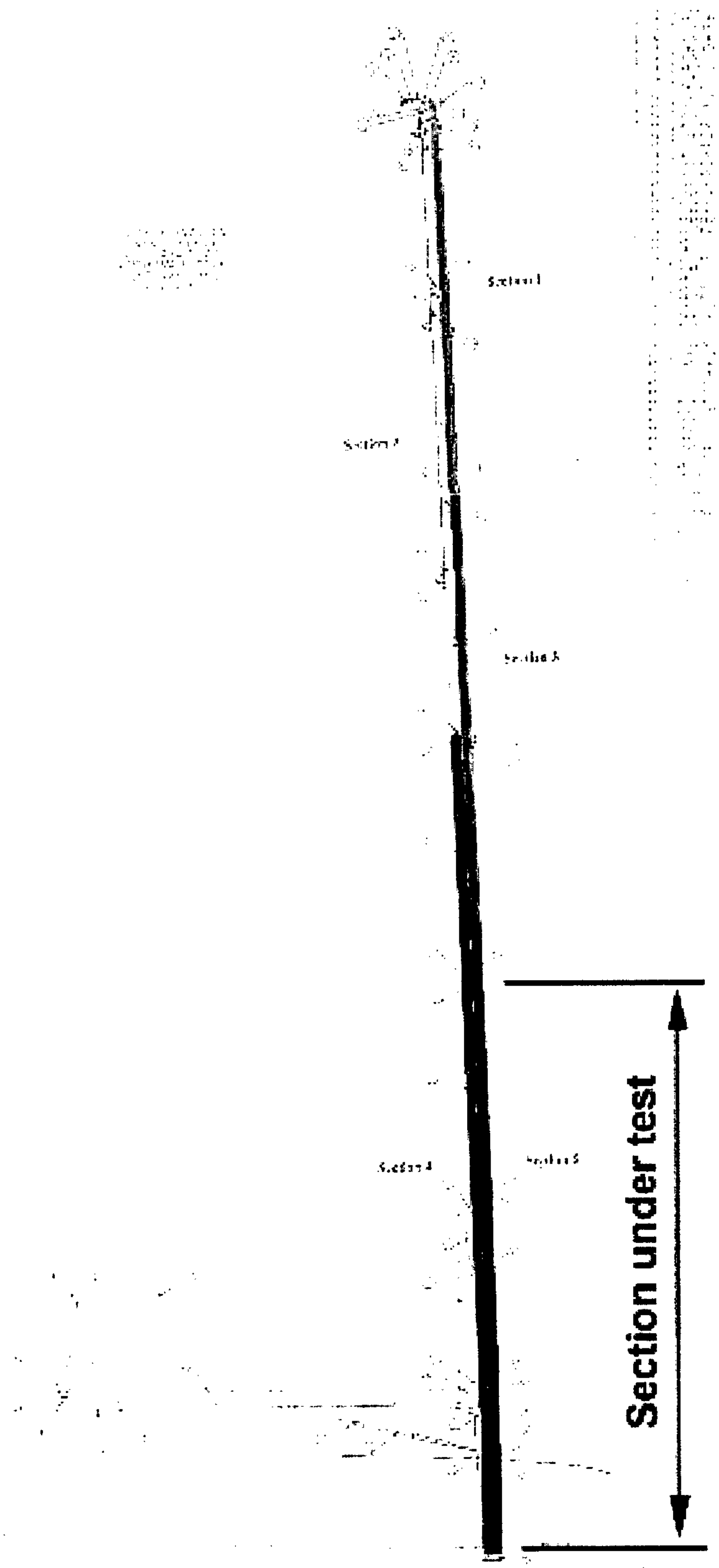
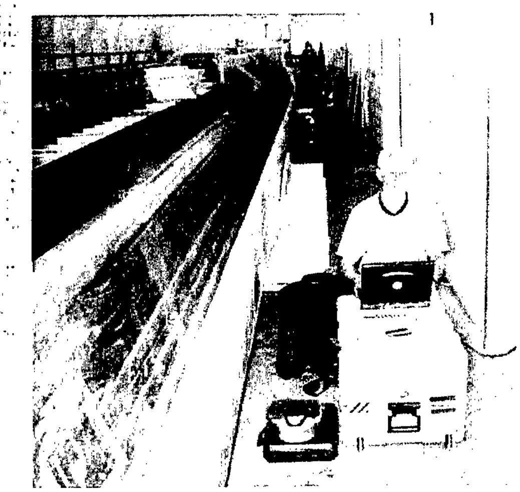


Figure 3. Drawing Showing the Section of the Mast that Was SIDER Tested



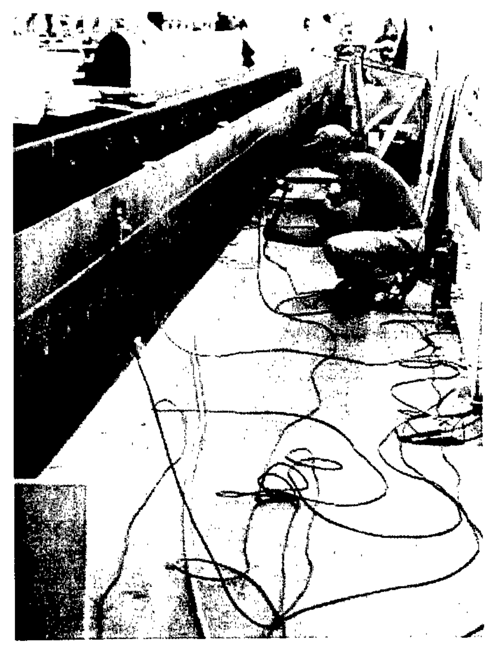


Figure 4. Mast during SIDER Testing

SIDER is the Structural Irregularity and Damage Evaluation Routine. The procedure looks at either the entire structure, or large parts of a structure, and identifies locations where there is variability in structural stiffness. These areas either are due to the design stiffness variability of the structure itself, or are manufacturing defects or in-service damage. After a preliminary SIDER, a follow-up SIDER can be used to show the change that has taken place over time. This change is attributable to damage occurring between the two examinations. For this particular project, the mast section was subject to a single SIDER. The design has a generally uniform stiffness, and therefore it was anticipated that the primary identified features would be coincident with the areas that had known manufacturing problems.

Grid

In order to conduct a SIDER analysis, the structure needs to be marked with a mesh of test points. For the best results, the mesh should be uniform. However, some irregularity is acceptable. For the mast section, it was decided to use a basic mesh size of nine inches in both directions. The nature of the structure meant that no variation in this mesh pattern was necessary.

The global origin for measurements was the base of the mast section, as shown in Figure 5. The X-direction was along (up) the mast. The Y-direction was the distance along the curved outer surface of the mast, with positive coordinates being assigned to test points on the starboard side of the mast. The Z-direction was normal to (and into) the mast surface. Using this style of coordinates and axes means that SIDER contour plots of the surface of the mast are planar, and can be presented in this report.

Figure 5. Global Origin

The overall length of the mast section was 120 feet. The part that was SIDER tested was from 59-feet 5-inches to 99-feet 2-inches from the mast base. Figure 6 shows the test grid with grid point numbering. In this figure, the bottom of the mast section is 59-feet 5-inches below the bottom of the figure (that is, below the row of grid points #12-#19).

Accelerometer Locations

Most SIDER tests use four accelerometers, arranged on a close-to symmetric pattern. The symmetry is deliberately broken so that the accelerometer locations are partly randomized. Additional transducers may be required if the structure is not particularly resonant. In this case, each transducer might not "see" the impact at all locations. It is generally best if at least four transducers "see" the impact at any point on the structure. For this study it was decided to use four accelerometers, since the structure was very resonant. Hitting the structure at any location caused motion which was detectable throughout the structure. As described later, the SIDER used the data from all accelerometers. All accelerometers had a nominal sensitivity of 100 mV/g.

The locations of the accelerometers are shown in Table 1. They can also be seen in Figure 7. The absolute location of the transducers is estimated to have an accuracy of ±1.5".

Accelerometers mounting bases were bonded with cyanoacrylate superglue to the outer surface. The accelerometers were then mounted by stud to the mounting bases.

Table 1. Location of the Accelerometers

Accelerometer	Analyzer Channel	X	Y	Z
A	2	63'11"	0'0"	0"
B	3	77'1"	-2'9"	0"
C	4	81'7"	1'6"	0"
D	5	84'11"	2'7"	0"

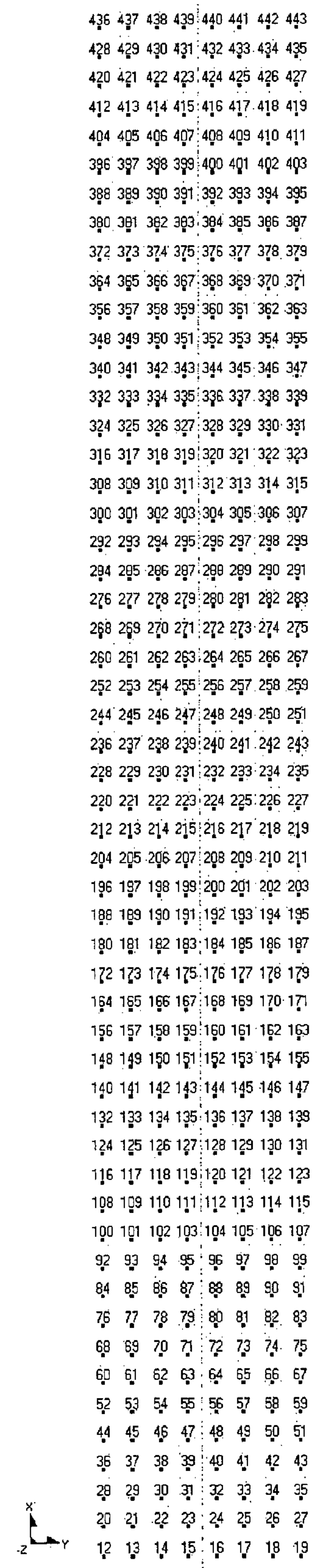


Figure 6. Test Grid for *Mirabella V* Mast Section

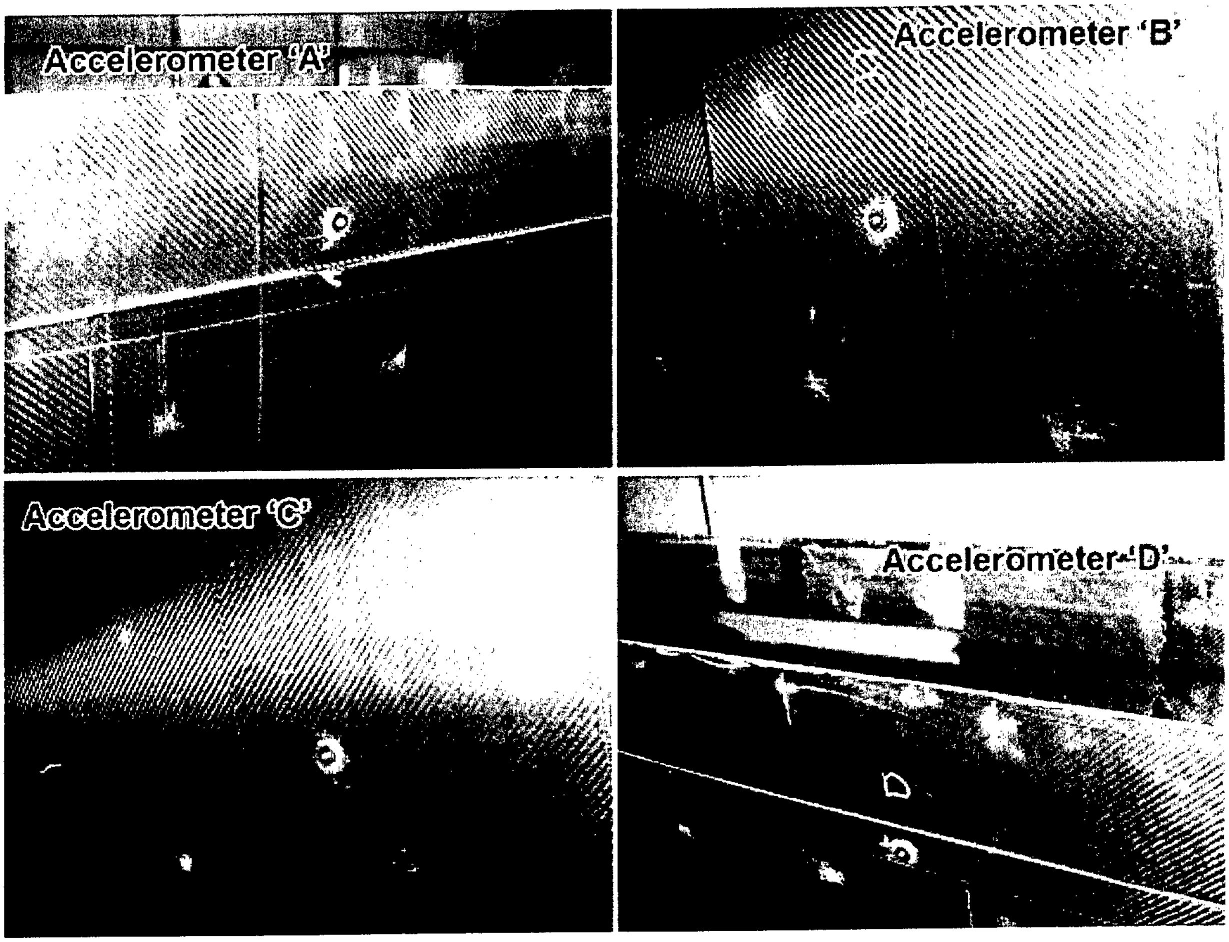


Figure 7. Accelerometer Positions

Data Acquisition and Quality

Excitation was with the modally, tuned, midsize sledgehammer with the gray tip. This is the second softest tip, and is typically used for resonant structures with low-frequency behavior. The impact excitation provided a sufficiently high level of energy up to about 250 Hz.

The data acquisition frequency range was 0-1000 Hz, with a resolution of 0.625 Hz. The response exponential window was optimized at 0.3 seconds. Data for each impact point were spectrally averaged for two hits. On site, the data quality was primarily assessed by observation of the individual coherence functions. When the coherence was atypically poor, the measurement was repeated until either the coherence improved, or it was assessed that the low coherence was a structural issue rather than a test issue.

After the fact, the data quality is assessed by the average coherence. Figure 8 shows the average coherence. In keeping with our standard procedures, the average coherence is shown separately for each transducer. In this way, instrumentation or local structural problems can sometimes be identified. Note that the Coherence axis for each graph is expanded, and only shows the range 80-100%. We would normally consider a high quality data set to have an average coherence in excess of 95%, and preferably more than 98%. We have very high-quality data up to about 250 Hz, as expected from the input energy frequency range.

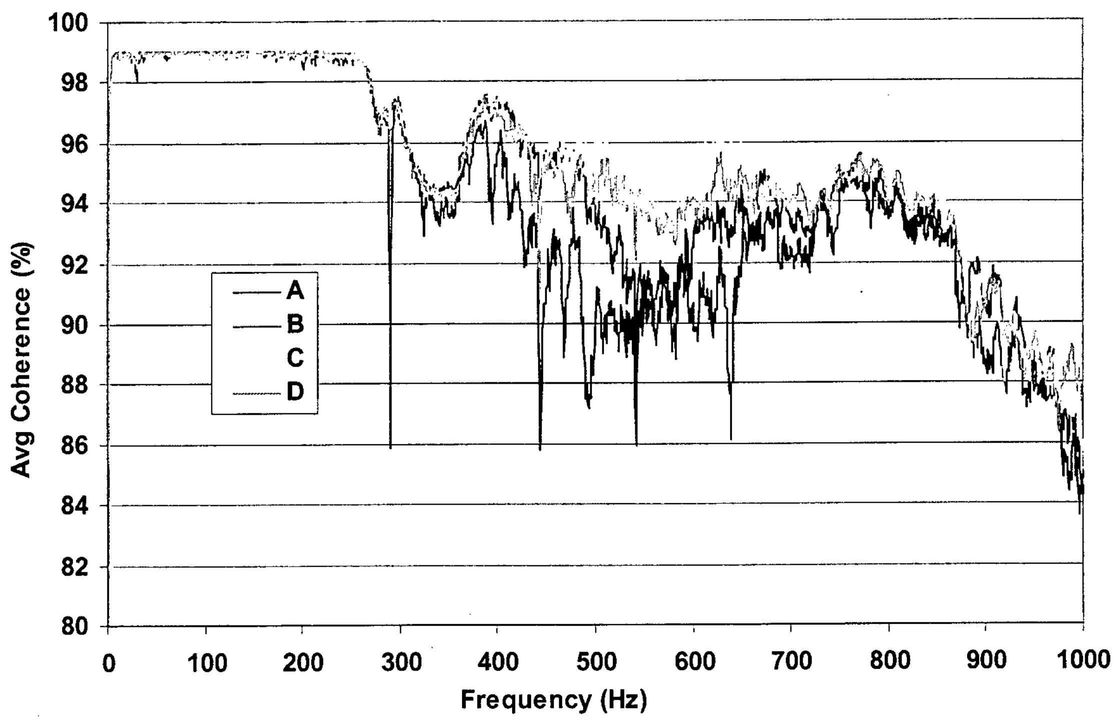


Figure 8. Average Coherence

The conclusion drawn is that all the transducers recorded data of a high quality, although, as is normally expected, the data at the highest frequencies have reduced quality. This is because the hammer impact did not put sufficient energy into the structure at these high frequencies to get the response signals sufficiently out of the noise threshold.

SIDER Test Results

Based on the coherence data, the SIDER analysis was conducted from 5 to 250 Hz, being a frequency range where the average coherence is above about 98%.

Figure 9 shows the SIDER contour plot. On this plot, the small crosses show the test grid and the axes legends show the distance in feet from the global origin. While SIDER is a directional test, the results shown here are solely for the up-down analysis. The analysis requires a reasonably large number of test points in the direction of the analysis. For this specific test, it was decided to limit the interest to the up-down analysis, and therefore the test grid was restricted in number of points in the 'circumferential' (Y) direction. This saved a significant amount of test time. This limitation was imposed because the mast has a very large aspect ratio.

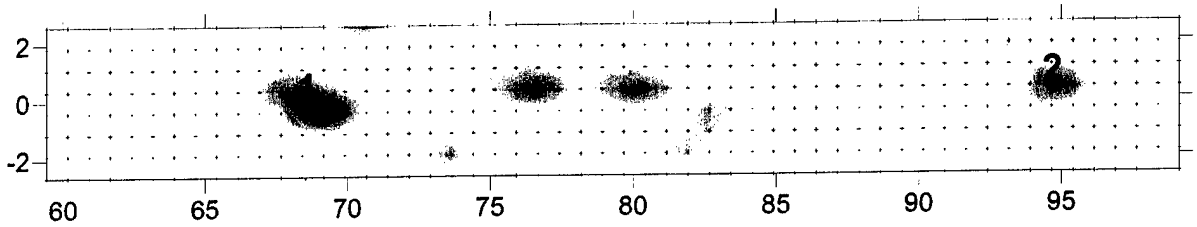


Figure 9. SIDER Contour Plot

Figure 10 and Figure 11 show contour plots overlayed on photographs of the inside of the mast. For each feature, there is a photograph showing the inside of the mast with white chalk marks showing the previously identified damage regions. The same photograph is then repeated with the SIDER results overlayed at the same scale as the photograph.

Note that the contour plots can be used to accurately locate features, whereas the foreshortening of the photographs means that features can be shown several inches from their actual position on the photographs.

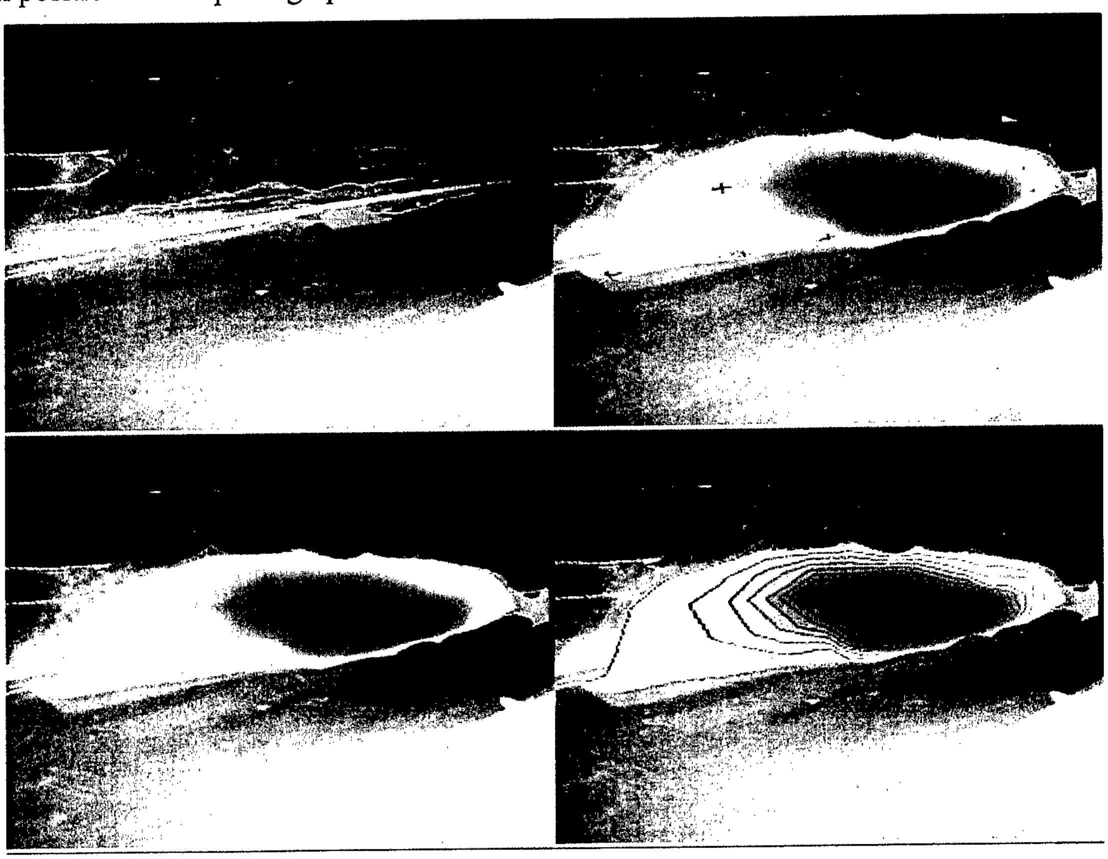


Figure 10. SIDER Results near Feature Number 1

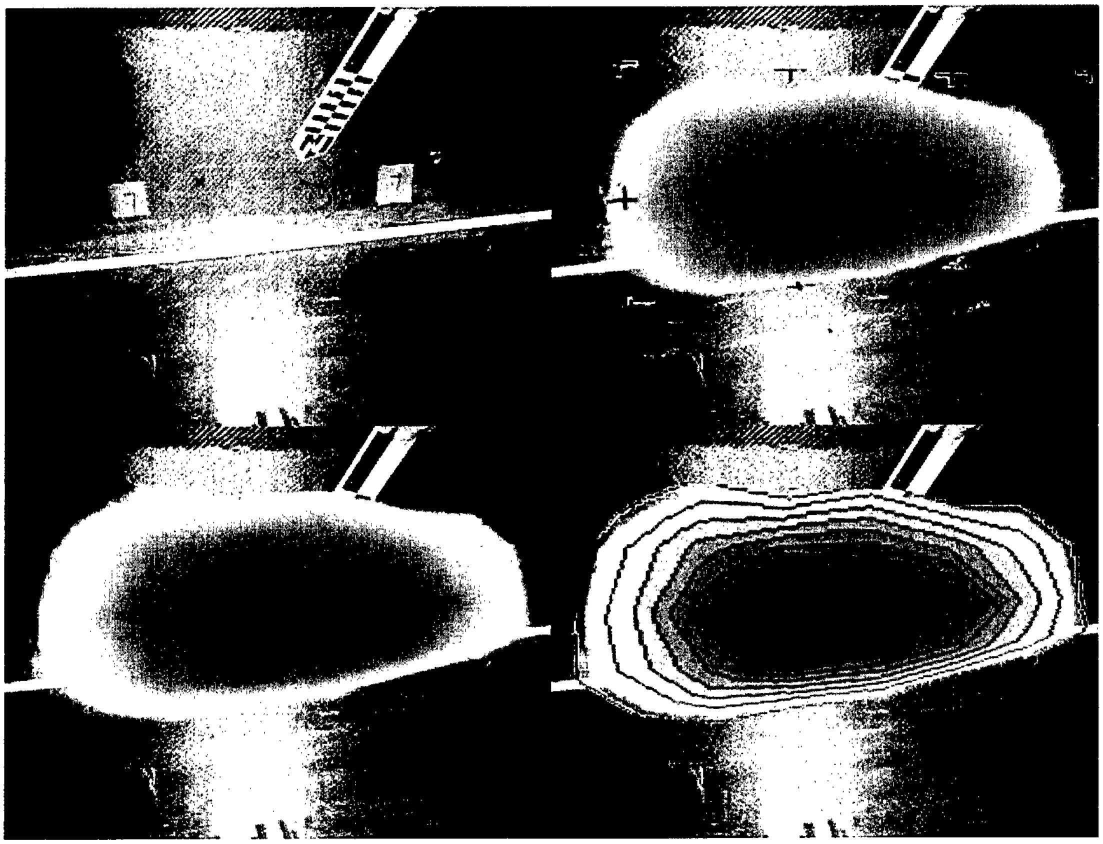


Figure 11. SIDER Results near Feature Number 2

Discussion of SIDER Results

SIDER is a directional test, and the results can best be interpreted with this in mind. For this specific test, it was decided to limit the interest to the circumferential Y-direction analysis, which is along the curved outer surface of the mast. This analysis will identify stiffness changes along the axis of the mast. Any feature, which is identified in this specific analysis, will be the result of manufacturing. It should also be mentioned that SIDER testing performed on the same structure before/after testing will identify changes happening during the time interval between tests.

There were two major features identified on the mast section, indicated by locations 1 and 2 on Figures 9. For location 1, there was a noticeable surface indication or bulge. The SIDER results correlated closely to what was visually seen on the inner surface. Although the damage was visible from the inside, there was no indication on the exterior of the mast. Since the testing was performed on the exterior, the significance of locating this anomaly from the exterior is noteworthy.

A section of the mast was also inspected using laser shearography. This technique was used to inspect areas of the mast that exhibited visible damage in an attempt to map out the extent of damage that was present. The damage located using SIDER correlated almost exactly with that determined using the laser shearograpy. In addition, the regions between 75 and 80 shown in Figure 9, which were also inspected using laser shearography also correlated well with the SIDER results. It should be noted that the SIDER indication shows that these latter areas were not as severe as locations 1 and 2. It is not known whether the laser shearography provide the same conclusions.

Location 2 showed no visible indication on either the interior or exterior of the mast section. The significance of this indication, however, was of the same magnitude as location 1 as seen by the intensity of the red color. The SIDER results are such that the larger the value, the more severe the anomaly. No further investigation was performed to try to determine the specific type of damage that was present.

Conclusions

The carbon fiber composite mast was a very reverberant structure. The time required for the structure to cease vibration after an impact excitation was much longer than other structures that we have tested in the past, typically taking a few seconds for vibration to damp out to the touch. Care must be taken with structures such as this to achieve high coherence for the frequency response functions.

The SIDER inspection was able to locate manufacturing anomalies that were visible as well as ones that showed no surface indication. Areas that were identified as having manufacturing anomalies by laser shearography were also identified using SIDER. Finally, SIDER provided a quantitative assessment of the areas where the manufacturing anomalies were located.